

LOW NO_x EXPERIENCES FIRING RESIDUAL OIL IN INDUSTRIAL BOILERS

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ABSTRACT

Residual oil continues to be the fuel of choice for many industrial steam users while environmental regulations allow its use. However, new emissions regulations on NO_x and SO_x are requiring substantial improvements in emissions performance or it will be regulated out of existence. This paper discusses the results and effectiveness of low NO_x design modifications to residual oil firing industrial boilers. Industrial package boilers have specific performance criteria that impede the effectiveness of such low NO_x techniques. Factors such as smaller furnaces, higher firing densities, lack of air preheat, widened operating envelope, simple controls, and variable fuel quality make the industrial package boiler a more challenging low NO_x environment than a field erected or utility boiler. This paper summarizes the results of this NO_x reduction program on several industrial water tube boilers, both package and field erected. The results indicate that significant NO_x reduction can be obtained through spray pattern modification to produce a staged spray flame with rich and lean zones. The resulting spray flame reduces both thermal and fuel NO_x production in cases where the furnace possessed sufficient volume to allow the increases in flame length and width resulting from the flame staging. These results indicate the effectiveness of NO_x reduction techniques is directly linked to the size and residence time in the furnace and the quality of the fuel. Reductions in NO_x of up to 25% can be obtained simply through judicious use of spray staging. The greatest NO_x reductions are obtained in field erected boilers with low firing densities as a result of the ability to stage the combustion. The variability in fuel characteristics such as viscosity, distillation curve, carbon residue, and ash composition limits the potential emissions reduction and maintaining stable combustion.

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INTRODUCTION

Heavy residual oil is the fuel of choice for industrial and utility boiler owners where natural gas and coal are not continuously available. Residual oil is an inexpensive liquid fuel with significantly lower operating costs than coal. Many regions within the United States have been designated Ozone Non-Attainment areas under the Clean Air Act Amendment and are under increasing pressure to reduce NO_x emissions. NO_x emissions reductions can be obtained by (1) switching to an alternate fuel with less propensity for NO_x production, (2) installation of flue gas treatment systems such as SCR and SNCR, and (3) installation of low NO_x burner equipment. The first option is not possible where natural gas or diesel oil are unavailable, such as in the Northeast United States. The second option, SCR or SNCR, is costly and prohibitive to many industrial boiler owners whom may choose to leave the United States where environmental restrictions are less stringent. The most cost effective option to reduce NO_x emissions from residual oil is the installation of low NO_x burner equipment of which the atomizer is an integral part. Many boiler owners find themselves very near to compliance levels of NO_x emissions and would like to achieve compliance through the most cost effective method. Coen has offered a low NO_x atomizer program where the typically uniform and symmetrical spray pattern shape of the atomizer is modified for rich-lean staging yielding significant reductions in both fuel and thermal NO_x production. This paper summarizes the results of several of these NO_x reduction studies in both field-erected and package water tube boilers.

Multiple Venturi MV Atomizer: The multiple venturi atomizer is an inside mix, twin fluid atomizer used for the combustion of liquid fuels from light oil up to heavy asphalt or pitch which require heating prior to atomization (see Figure 1). Liquid fuel passes through the central fuel tube, surrounded by the steam tube, until reaching the multiple venturi mixer where a two-phase mixture is produced. This mixture is forced through a nozzle body to increase its momentum prior to exiting through a plain-jet cap. The cap design of the MV allows great flexibility for flame shaping through the cap drilling pattern. Four different sizes of the MV atomizer are used to achieve capacity ranges from 1 to 40 gallons per minute fuel flow.

BACKGROUND

NO_x is the term typically used to refer to NO, and NO₂ formed as by combustion. It is estimated that the majority of global NO_x is naturally occurring. Significant natural sources are lightning, forest fires, and bacterial action. Of the anthropogenic sources, approximately 55% are from stationary sources, and the remainder from mobile sources. Although man-made NO_x sources are a small portion of the global NO_x, they tend to be concentrated in urban areas resulting in excessive production of ozone. Of the NO_x formed during combustion in industrial boilers, 95+% will be emitted as NO, and less than 5% will be NO₂. The NO, however, is readily converted to NO₂ in the presence of atmospheric radiation. NO₂ is a reddish-brown gas, toxic, and corrosive.

The two sources of nitrogen for the formation of NO_x are atmospheric N₂ (forms thermal NO_x), and nitrogen atoms organically bound to the fuel being fired (forms fuel NO_x). The thermal and fuel NO_x formation mechanism are outlined below.

The thermal NO_x mechanism is initiated with the high temperature disassociation of atmospheric N₂ molecules. Atmospheric nitrogen has a triple atomic bond, and is extremely stable. Atmospheric nitrogen will only decompose at the very high temperatures within the flame. Thermal NO_x is therefore very temperature dependent. The resultant nitrogen atoms are unstable and will precede rapidly to form either NO or a new N₂ molecule. For fuel lean combustion, the Zeldovich mechanism is accepted as an approximation of NO_x formation.



In staged combustion, thermal NO_x is minimized by:

1. Reducing Peak Flame Temperatures,
2. Reducing the Oxygen Levels at the Peak Flame Temperatures,
3. Reducing the Time of Exposure to the Peak Flame Temperatures.

For fuels such as residual oil, the oxidation of nitrogen that is organically bound to the fuel molecule becomes the primary source of total NO_x emissions. For this reason overall NO_x reduction efforts are geared toward reducing the conversion of fuel bound nitrogen (FBN) to NO_x. Recall that in thermal NO_x formation, the nitrogen source is the extremely stable (triple atomic bond) atmospheric nitrogen. The source of nitrogen for fuel NO_x is actually single bonded directly to the fuel oil molecule. As the fuel burns, all bound nitrogen disassociates to form highly unstable nitrogen radicals. These nitrogen radicals will either be oxidized to form NO_x, or bond with another nitrogen radical to form N₂ (atmospheric nitrogen.) To minimize the oxidation of FBN, we try to delay mixing of stoichiometric air. The less oxygen available to the nitrogen radicals, the more the reaction will favor the formation of N₂. The desired result are long, narrow flames with fuel rich zones to inhibit the conversion of FBN to NO_x. Ideally, the combustion reaction will not be complete until just before the gasses turn into the convection tube bank.

Thermal NO_x and Fuel NO_x are both being formed in the combustion reaction. Although the formation mechanisms are widely different, minimization techniques are similar. The long fuel rich flame established to minimize FBN oxidation also lowers the flame temperature and reduces thermal NO_x. The delayed mixing of stoichiometric air also reduces the amount of atmospheric nitrogen available at the peak temperature zones at the base of the flame.

Table I: NOx Testing Results

Boiler	Boiler Capacity (lb/hr stm) (MBtu/hr)	Boiler Type	Burner Equipment	%N in Fuel	NOx Original	NOx Results Low NOx	NOx Reduction
A	90 108	field erected	2 burners	0.45	0.266	0.202	24%
B	120 145	field erected	1 burner	0.35	0.369	0.277	25%
C	85 100	package	1 burner (530°F air)	0.49	0.35	0.32	9%
D	100 115	field erected	1 burner	0.34	0.460	0.360	22%
E	100 115	field erected	2 burners	0.45-0.53	0.312	0.270	13%
F	100 115	package	1 burner	0.45-0.53	0.360	0.360	0%

Residual oil contains a significant amount of fuel bound nitrogen which can contribute more than 50% of the total NOx emissions. Low NOx residual oil techniques require the reduction of the conversion of fuel bound nitrogen to NOx in addition to thermal NOx. Figure 2 illustrates the great potential for fuel bound NOx generation and the typical effects of FBN on NOx emissions.¹ Previous research has shown that rich-lean spray staging has great potential for reducing fuel NOx production from residual oil flames.^{2,3} The greatest limiting factor to rich-lean staging in residual oil spray flames is the generation of particulate matter. As the oil droplet vaporizes in the furnace, a hollow cenosphere of carbonaceous material is formed whose diameter and mass are dependent upon the original oil droplet diameter and the quantity of coke forming carbon in the original fuel.^{4,5} Any successful low NOx atomizer must meet current particulate requirements. By using the Coke Formation Index (CFI) relationship, the expectant coke particle diameter can be calculated from the original droplet diameter as shown in Figure 3. The oxidation of these particles is based on surface combustion of carbon and the expected burnout for various particle sizes at typical furnace oxygen and temperature conditions is shown in Figure 4. Finally, Figure 5 illustrates that the smaller droplets generate small coke particles which have sufficient residence time to oxidize completely. This figure also demonstrates that the dominant particulate emissions arise from the large original droplet sizes. This analysis demonstrates that attempts to produce fuel rich zones of combustion with large droplet diameters results in increased particulate emissions.

RESULTS

Boiler emissions testing initiates with an inspection of the existing boiler and burner equipment to determine if any repairs are required. A set of baseline emissions data are obtained to determine the “as found” emissions of the boiler. The original equipment is then optimized to reduce burner excess air levels and obtain the best NOx and CO performance. These optimized data are then used as the baseline for comparison with new low NOx atomizer caps. Several low NOx atomizer caps are then test fired to determine their performance. The most promising cap is then optimized

over the full firing range of the boiler and the NO_x emissions are compared to the optimized baseline data.

Over ten of these NO_x reduction studies have been performed and a sampling of the results are provided in Table I. The greatest NO_x reduction from the optimized baseline was 25% from a single burner, field erected unit firing at 145 MBtu/hr. Most of the field erected boilers experienced significant NO_x reductions from the optimized baseline with the use of rich-lean staged atomizer caps. However, the package boilers proved to be the most challenging application of staged caps with spray impingement on the boiler side walls limiting the degree to which the spray flame can be staged for NO_x reduction. A typical set of emissions data are provided in Figure 6 from Boiler A in Table I. This boiler uses two burners, side by side, to produce up to 90,000 lb/hr of steam flow. The original atomizer equipment data shown in Figure 6A) illustrate the effects of optimization on NO_x and CO emissions as combustion is improved through optimization of burner excess air. The NO_x emissions increase with increasing firing rate to a maximum of 0.266 lb/MBtu NO_x (@3% O₂, dry) after the optimization. The emissions data for the best performing low NO_x atomizer caps indicate significant emissions improvement over the entire operating range with a maximum NO_x emission of 0.202 lb/MBtu.

CONCLUSIONS AND OBSERVATIONS

- Significant NO_x emissions reductions for boilers firing residual fuel oil can be achieved through relatively inexpensive fuel spray modifications.
- Fuel staging in residual fuel oil spray flames results in reductions of both thermal and fuel NO_x.
- Significant NO_x reduction results are achieved in field erected boilers where generous furnace dimensions allow the increased flame volume of a highly staged residual oil flame. NO_x reductions in package boilers with staged spray flames are inhibited due to flame impingement on the boiler walls.
- Further research is required to determine the effects of droplet diameter on fuel NO_x conversion in practical residual fuel oil fired boilers. Additional understanding of particulate reduction in low NO_x residual oil flame is also required.

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REFERENCES

1. Pershing, D.W., Cichanowicz, J.E., England, G.C., Heap, M.P., and Martin, G.B., "The Influence of Fuel Composition and Flame Temperature on the Formation of Thermal and Fuel NO_x in Residual Oil Flames," *Seventeenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 715-726 (1978).
2. Beér, J.M., Jacques, M.T., Farmayan, W., and Taylor, B.R., "Fuel-Nitrogen Conversion in Staged Combustion of High Nitrogen Petroleum Fuel," *Eighteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 101-110 (1981).
3. Hanson, S.P., Beér, J.M., and Sarofim, A.F., "Non-Equilibrium Effects in the Vaporization of Multicomponent Fuel Droplets," *Nineteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 1029-1036 (1982).
4. Urban, D.L., and Dryer, F.L., "New Results on Coke Formation in the Combustion of Heavy-Fuel Droplets," *Twenty-Third Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 1437-1443 (1990).
5. Urban, D.L., Huey, S.P.C., and Dryer, F.L., "Evaluation of the Coke Formation Potential of Residual Fuel Oils," *Twenty-Fourth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 1357-1364 (1992).

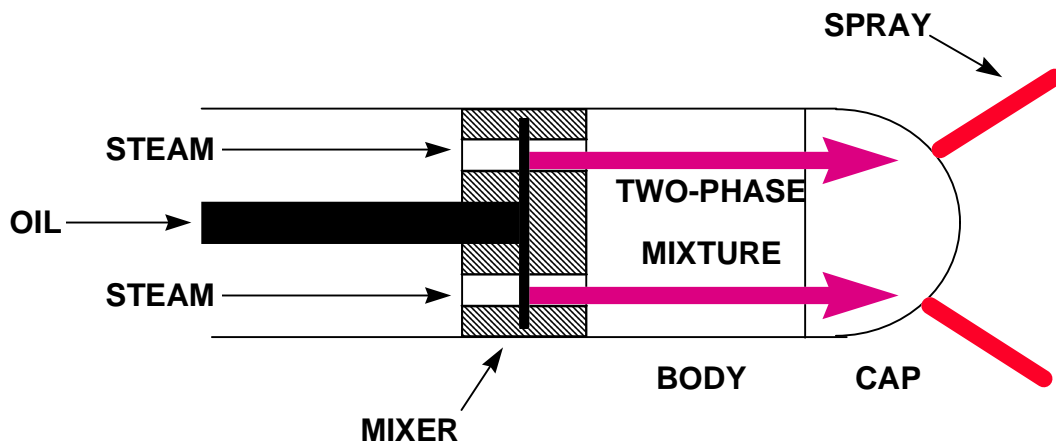


Figure 1: The Multiple Venturi Atomizer

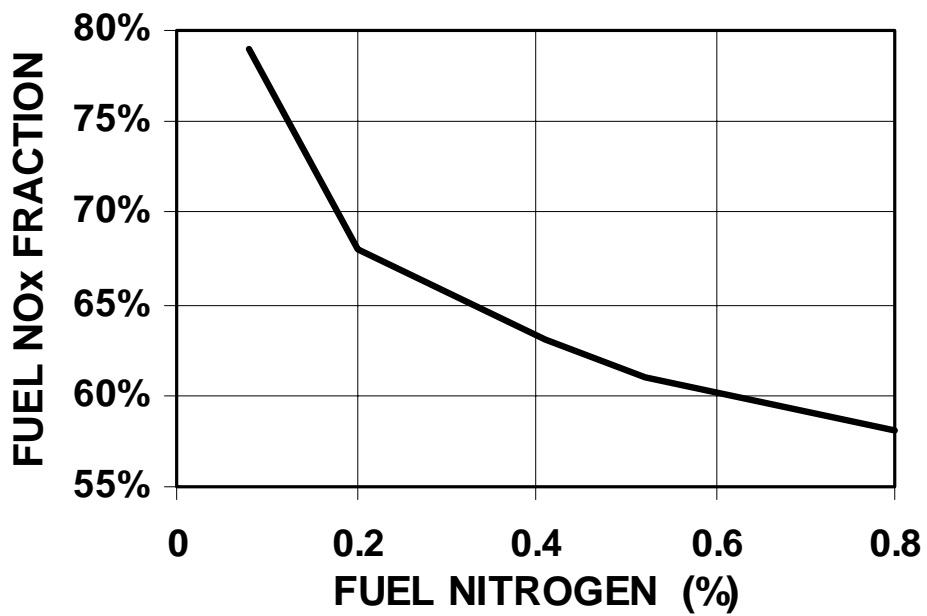
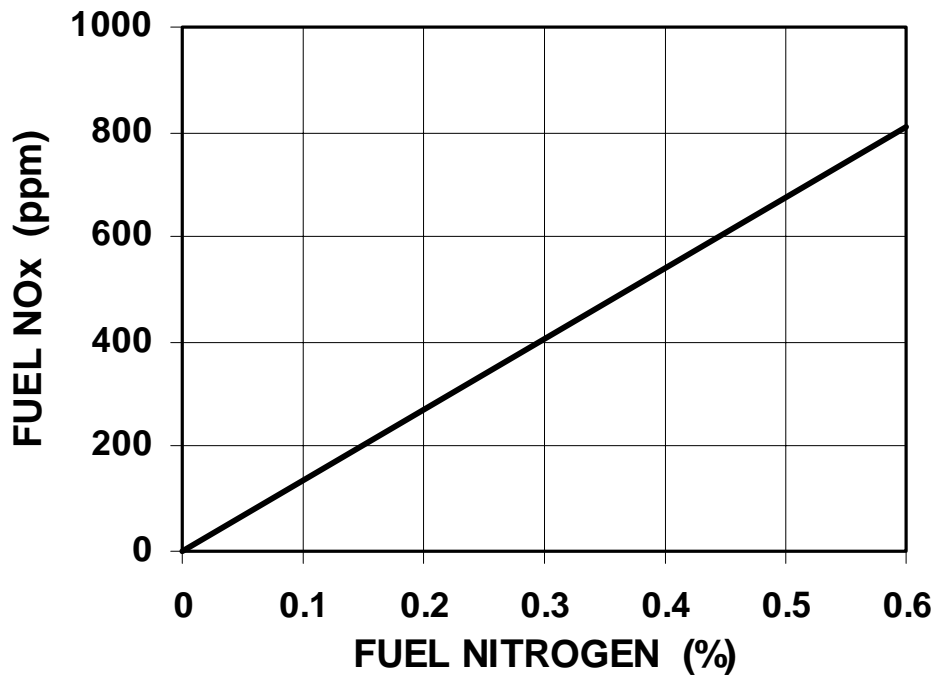


Figure 2 a) and b): Effects of fuel bound nitrogen on total fuel NOx produced and fractional fuel nitrogen conversion (Pershing, et al; 1978)

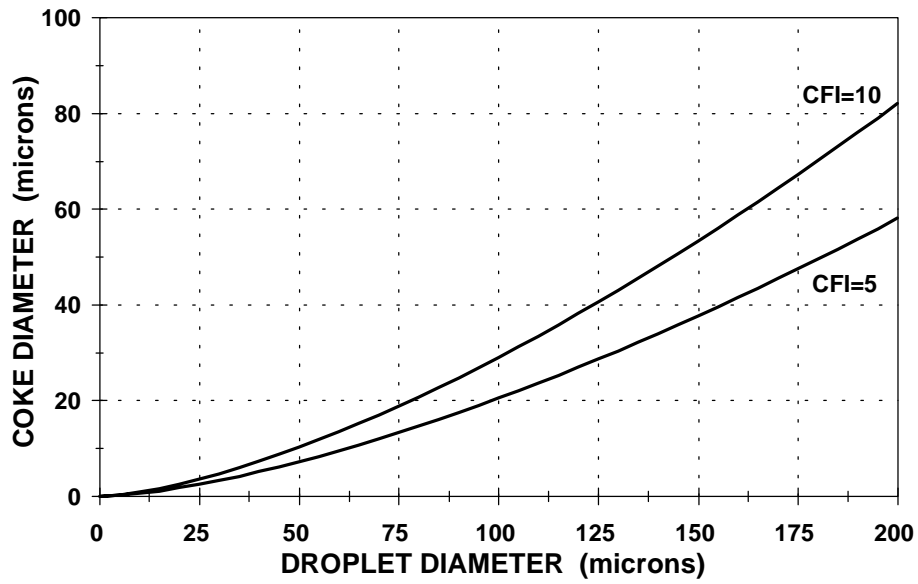


Figure 3: Predicted coke particle diameter based on original droplet diameter

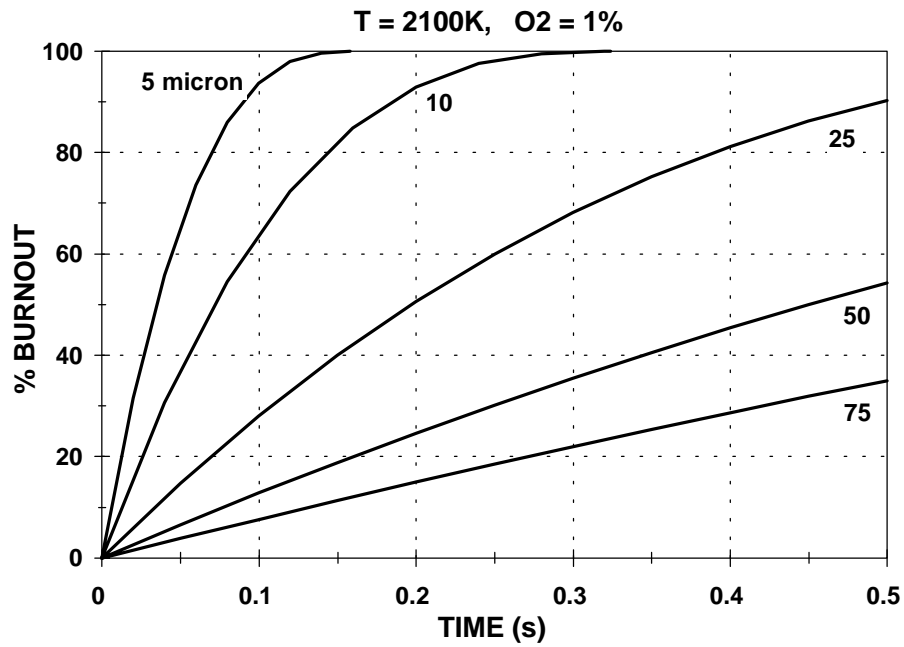


Figure 4: Predicted coke particle burnout based on time, temperature and oxygen concentration

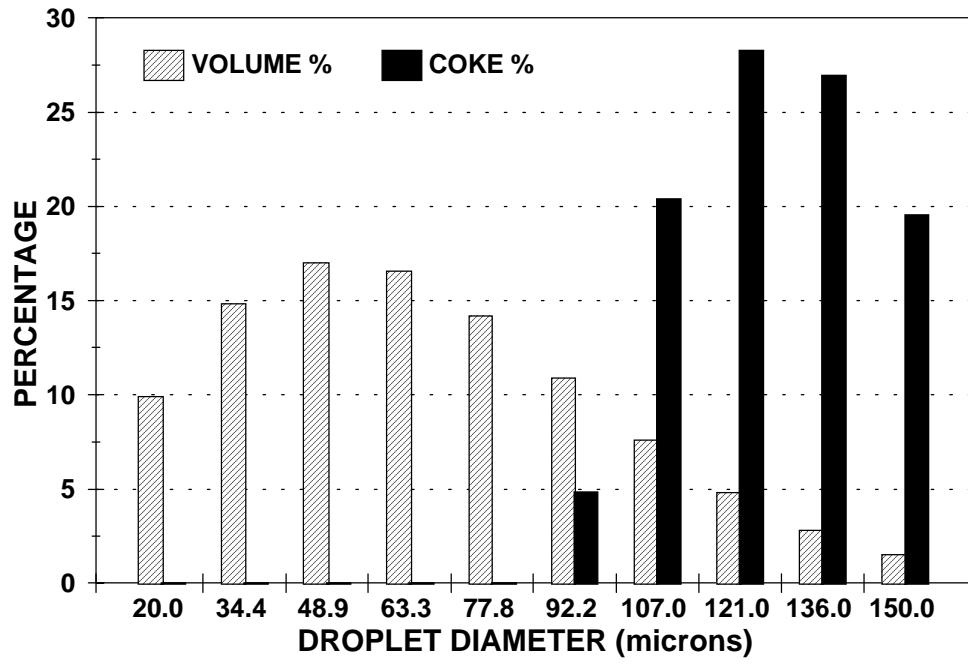
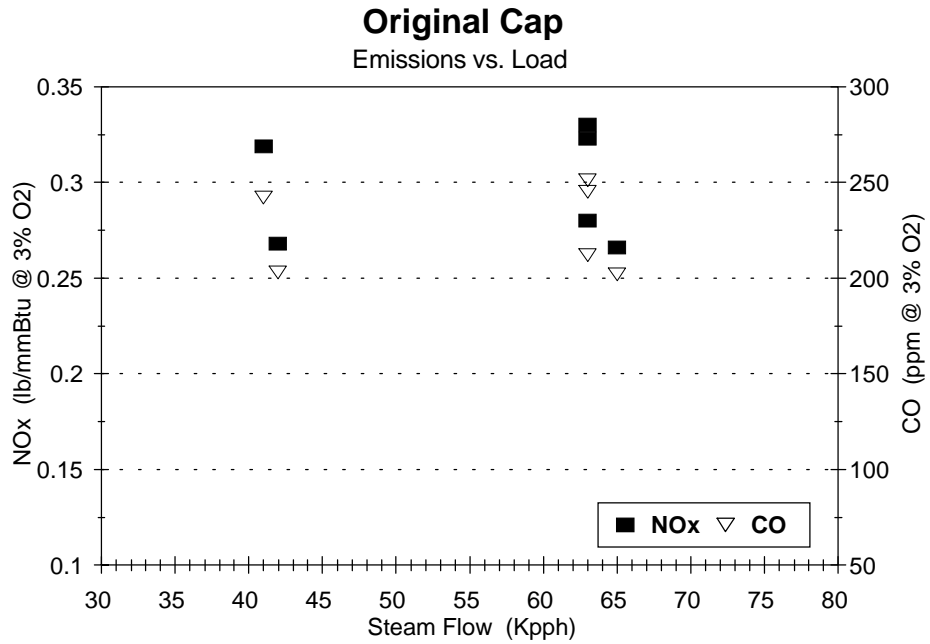
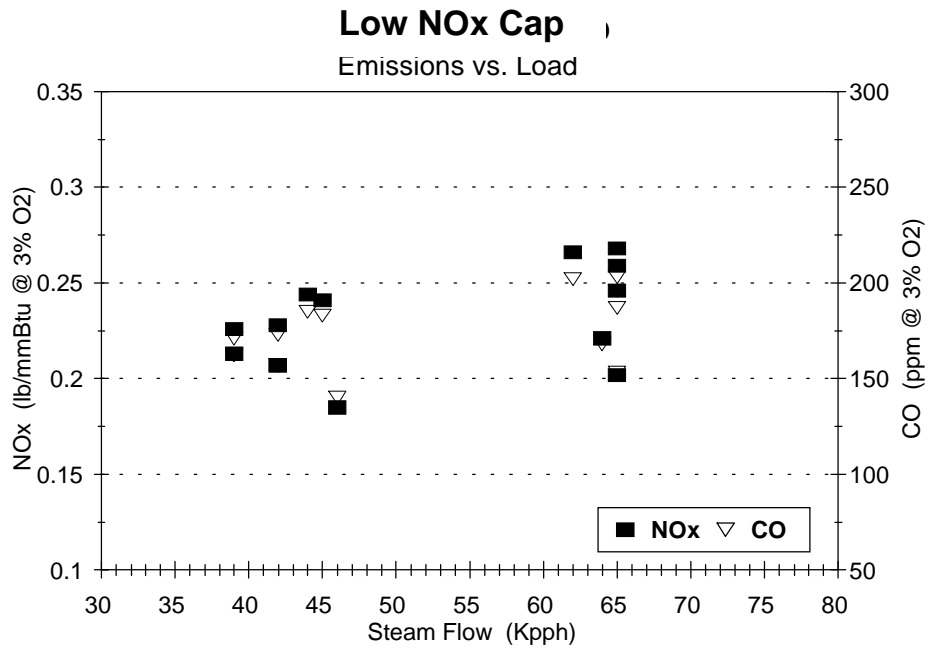


Figure 5: Predicted particulate mass emissions based on original droplet size distribution

A)



B)



Figures 6 A) and B): NO_x emissions results for boiler A